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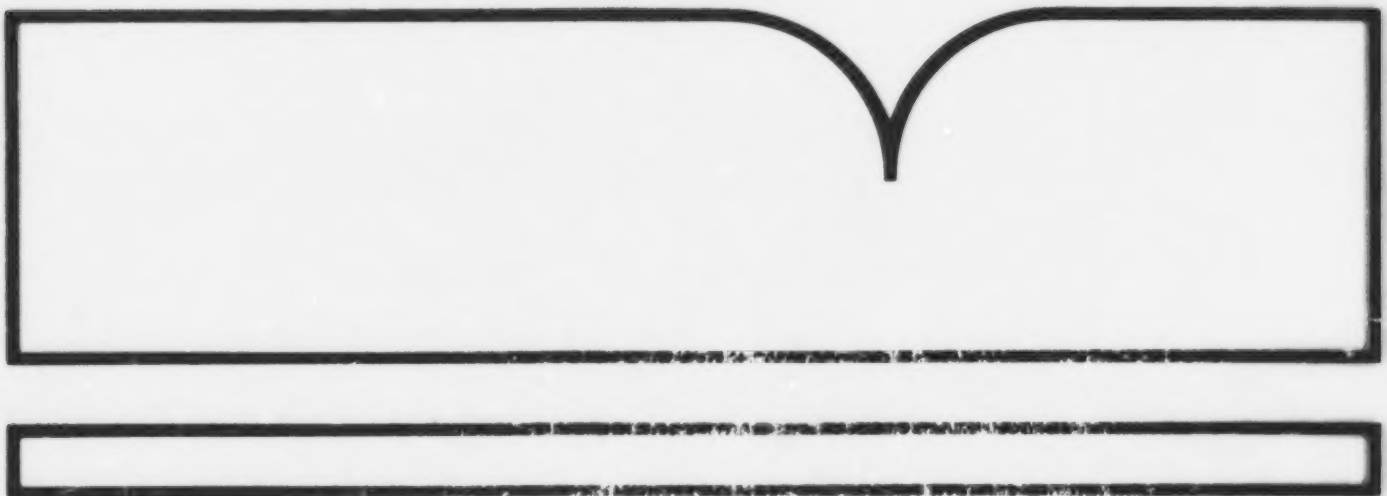
Surface Heat Flux Derived from Sodar
Amplitude and Frequency Data: A Comparison

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by

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16. ABSTRACT Sensible heat flux measurements were made in an agricultural setting near Champaign, Illinois by using doppler sodar, eddy correlations and profile methods during convective conditions during an experimental study called VOICE, (Vertical Observations Involving Convective Exchange). This paper presents details of the analyses which compares the heat flux measurements by these three techniques. The sodar data represents volume average estimates while the other two standard techniques are point time measurements. The results for these three methods are comparable but sodar estimates show wide variability during the midmorning time period compared to the other techniques.		
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SURFACE HEAT FLUX DERIVED FROM SODAR AMPLITUDE AND FREQUENCY DATA:
A COMPARISON

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1. INTRODUCTION

The structure of the atmospheric boundary layer is known to undergo large diurnal variations that are critically important in processes such as the diffusion and dispersion of pollutants, development of convection and rainfall, and the air-surface exchange of momentum, moisture, and trace substances. The main forcing function for these developments is the surface heat flux, which in turn is a function of solar insolation, albedo, large-scale advection, heat capacity and emissivity of the surface, and the nature of the vegetative cover. Estimates of the flux of energy from the earth's surface to the atmosphere clearly are important for the operation of models attempting to predict the daily development of the planetary boundary layer (PBL).

As part of an effort to identify and investigate the modification of the Planetary Boundary Layer (PBL) by cumulus clouds and the interaction of the PBL with developing cumulus convection, Argonne National Laboratory investigated the convective PBL, in particular, thermal plume development and interaction with cumulus clouds. An important process controlling cloud evolution is the vertical transfer of energy input from the earth's surface into the

cloud layer. Thus, the determination of the surface heat flux on a physical scale relevant to the height of the mixed layer, and a time scale relevant to thermal plume and cumulus cloud development is a necessary first step in the process.

Measurements of surface heat flux in simple terrain can be made relatively easily using eddy-correlation techniques to measure the correlation of vertical velocity w and temperature T at a point within the surface layer. However, in complicated terrain or for estimates above the surface layer, a volume or area average is a potentially more useful estimate since the uncertainties introduced by inhomogeneities and statistical variability are reduced. In this experiment the terrain was relatively flat in all directions, with an alternating pattern of crops, usually soybeans and maize. The estimates of heat flux were made over a field of grass located within this "checkerboard" pattern (Figure 1). Hence measurements above the surface layer by the sodar will be more sensitive to the larger scale crop pattern than those near the surface.

The surface heat flux has been estimated previously from the temperature structure parameter, C_T^2 (Neff, 1975; Coulter and Wesely, 1980), and from estimates of the variance of vertical velocity σ_w (Weill et al., 1980). This paper compares these techniques with eddy correlation point estimates made under convective conditions in the VOICE (Vertical Observations Involving Convective Exchange) experiment near Champaign, Illinois, USA, in cooperation with the Dry Deposition Intercomparison Experiment (DDIE), which supplied complete measurements of surface layer parameters including winds, temperatures, humidities, sensible heat flux H_c , and latent sensible heat flux $L_w E$.

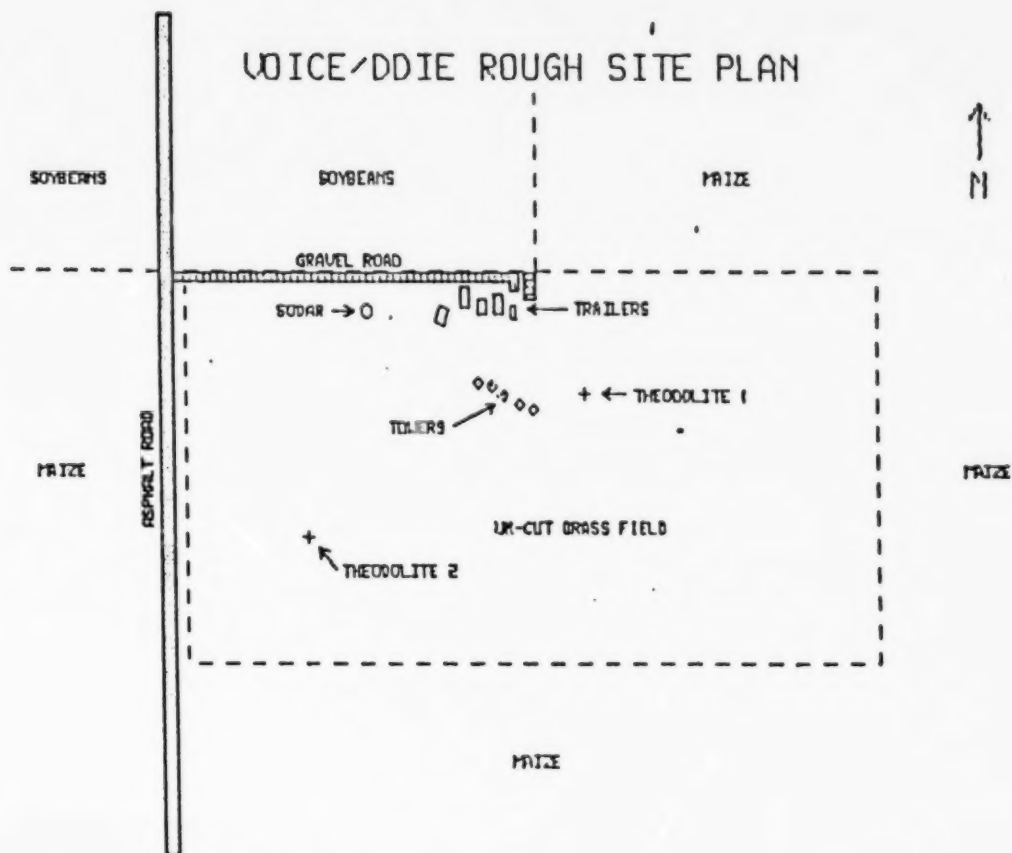


Fig. 1. A plan view of the experimental site for the VOICE experiment in June, 1982.

2. THEORY

Several investigators (Neff, 1975; Coulter, 1977; Mouldsley et al., 1981) have suggested the possibility of determining surface sensible heat flux from sodar-derived profiles of C_T^2 in the convective boundary layer through of the surface layer parameterization of Wyngaard et al. (1971):

$$C_T^2 = 2.68(\bar{T}/g)^{2/3}(H_p/(pc_p z))^{4/3}, \quad (1)$$

where $\bar{T}$ is the average absolute potential temperature g is the acceleration due to gravity, ρ is air density, c_p is the specific heat of air, and z is height. In fact, the existence of a $z^{-4/3}$ dependence of C_T^2 in the PBL has often been observed and can be used to verify the existence of unstable convective conditions dominated by buoyancy. Coulter and Wesely (1980) investigated this relationship and found that for estimates of surface heat flux derived from profiles of C_T^2 measured with sodar, it is necessary to include the effects of water vapor in the estimate of both C_T^2 and H_p through the relationship:

$$H_p = 0.48 \rho c_p (g/\bar{T})^{1/2} (2\bar{T}C_n)^{3/2} z\gamma_p, \quad (2)$$

where C_n is the acoustic refractive index parameter given as:

$$C_n = C_T(2\bar{T})^{-1}[1 + (0.06/B)^2]^{1/2}, \quad (3)$$

and

$$\gamma_p = \{[1 + (0.07/B)^2]/[1 + (0.06/B)^2]\}^{3/4}(1 + 0.07/B_s)^{-1}. \quad (4)$$

Here β_s and β are Bowen ratios, defined as the ratio of sensible heat flux to latent heat flux for the surface layer and for local regions aloft, respectively. Except for very small values of β , γ_p can usually be approximated by $(1 + 0.07/\beta_s)^{-1}$. In this experiment β_s was evaluated from eddy-correlation estimates of H_c and $L_w E$.

Weill et al. (1980) investigated the possibility of estimation of the heat flux profile by use of a scaling relationship,

$$\sigma_w^3 = \zeta z \frac{g}{\bar{T}} \overline{w'T'} \quad (5)$$

in dry convective conditions in the PBL. The term ζ represents a numerical factor equal approximately to 1.7. This, like eq. (1) is an apparently successful extension of surface layer parameterizations to the PBL. Solving for heat flux, we obtain:

$$H_v = \rho c_p \frac{\bar{T}}{g} \sigma_w^3 (3z)^{-1} . \quad (6)$$

It should be noted that the water vapor contribution to buoyance has been neglected in eq. (6); to include it, the term $(1 + 0.07/\beta_s)^{-1}$ should be added as a multiplicative factor to the right-hand side of the equation. Weill et al. indicate that mechanical production of turbulence contributes substantially to the vertical velocity variance estimate very near the surface, so that this region should be overlooked. Assuming that the heat flux is a linearly decreasing function of height allows the extrapolation of the profile of σ_w^3/z to the top of the surface layer, where the flux is constant with height. The height corresponding to zero heat flux is a first order approximation since eq. (6) does not include entrainment effects near

the top of the mixed layer. Thus, as for the profile estimate, one must first determine the existence of the proper shape of a profile of some sodar-measured parameter (in this case σ_w^3/z). Once that is determined, the heat flux estimate is straightforward.

3. OUTLINE OF METHODS

The site for these measurements was located in central Illinois and was a flat, grass-covered field surrounded by soybeans and maize to the north, and by maize to the west, south, and east (Fig. 1). The sodar was positioned along the northern boundary of the field, some 300 m from a row of instrumented towers and a maintenance shed. This is in contrast to previous measurements (Coulter and Wesely, 1980), which were in gently rolling, partially wooded terrain approximately 25 mi SW of Chicago, IL, and Lake Michigan; the local terrain was rather homogeneous but mesoscale circulations associated with Lake Michigan could have occurred at times.

The sodar at the present site used an antenna placed 1 m above the surface in a trailer with an enclosure 2.4 m high, and was operated at a frequency of 1275 Hz with a 100 Hz bandpass filter. The eddy-correlation measurements were taken at the easternmost tower, some 400 m from the sodar.

Data recorded by the sodar included signal amplitude and Doppler shift (evaluated using either complex covariance or an octant-crossing technique) usually averaged over 20 s and 10 m for amplitude analysis or 40 m for frequency. In addition, the signal-to-noise ratio and variance of vertical velocity averaged over 40 m were computed. For selected periods, the raw signal digitized at 200 s^{-1} was stored on a cartridge tape recorder. Because this study was part of an investigation into cloud exchange processes, data on

cloud height and position were obtained from use of two theodolites and a vertically pointing time-lapse camera located near the sodar. Eddy-correlation measurements were made using a fast-response vertical propeller anemometer together with a fine wire resistance thermometer for sensible heat flux and a Lyman-alpha hygrometer for latent heat flux.

The sodar amplitude data were averaged over periods of one hour in order to minimize variability caused by the influence of individual thermal plumes. A plot of $\log C_T^2$ versus $\log z$ was inspected to ascertain the presence of a $-4/3$ slope as outlined in Coulter and Wesely (1980). If the slope of a least squares line was within $\pm 1/16$ of $-4/3$, the data were deemed acceptable and the least-squares line was used to define the value of C_T^2 at a height of 100m, which was then used to determine a preliminary value of H_p . This value was then adjusted for water vapor contributions via eqs. (2-4). In the previous measurements of Coulter and Wesely there was no direct measurement of latent heat flux — rather, an indirect estimate was derived with assumptions about the surface energy balance and measurements of the net radiation and sensible heat flux.

The vertical velocity variance estimates were determined in a similar manner. One-hour averages of σ_w^3/z were calculated from the stored variance data. Each hourly profile was inspected to determine if there was a linear portion through the lower PBL. Obvious contamination by mechanical turbulence in the lowest levels was ignored and the least-squares fit to the selected points was then used to define the intersection at the surface and hence H_v .

Eddy-correlation estimates of H_c and $L_w E$ were provided in half-hour estimates, which were combined to provide one-hour estimates for comparison. Occasional missing data for individual half-hours were reconstructed by simple linear interpolation.

4. RESULTS

Weather conditions throughout the period were generally warm and humid with thunderstorms occurring during some afternoons. In these conditions, latent heat corrections to the profile estimates (H_p), while significant (10-20%), were not enormous.

Figure 2 shows daily variations of surface heat flux as determined by the three methods. In general the daily trend is present with both the variance and profile methods. Values through application of the profile method remain high compared to correlation estimates in the morning hours on many of the days. There are, however, days (June 20,21,29) where the agreement is good throughout the day. In this experiment the days with reasonable profile values during morning hours occurred in conditions of northerly winds and clear skies with little turbidity. In the remaining cases the values in the morning were usually about 50% greater than eddy-correlation values, although 100% differences were seen very early on June 23 and June 26.

Variance estimates showed no indication of excessively large values during morning hours, with the exception of June 23. Rather, variance estimates of heat flux appear to be biased slightly low compared to eddy correlation, particularly on June 21,25 and 29. Both variance and profile estimates are about 50% lower than eddy-correlation values on June 18.

Figure 3 is a comparison of the three techniques for surface heat flux estimation and Table 1 lists relevant statistics of the comparison. A one-to-one correspondence is not expected, particularly between the point sensor and either of the other two methods. Although the differences among the relative correlations are not large, it is somewhat surprising that the poorest correlation is between the profile and variance techniques, in spite of the fact that volume-averaging effects are identical for the two methods.

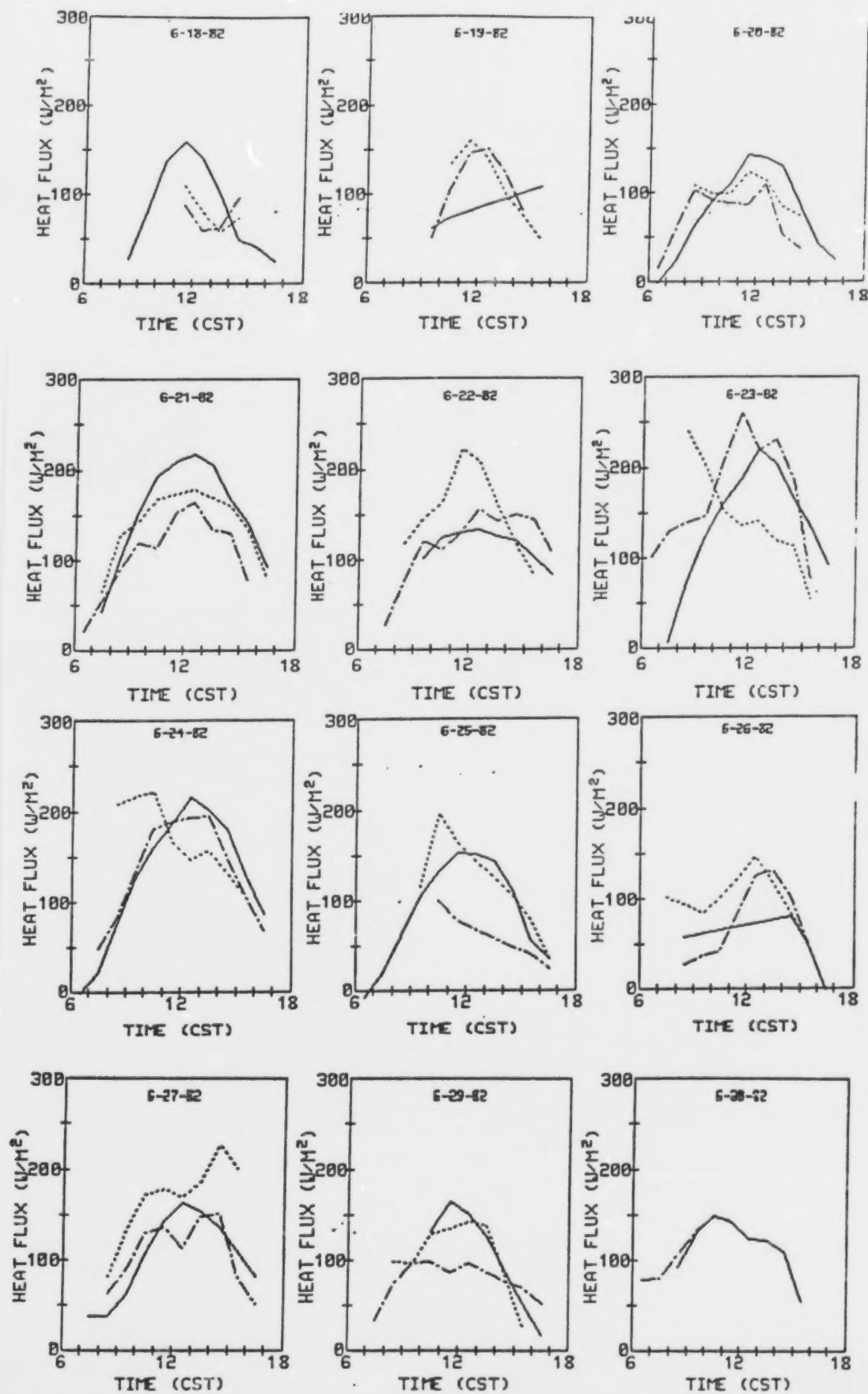


Fig. 2. Daily comparison of heat fluxes from the three measurement techniques for twelve days: Eddy Correlation (—), C_T^2 Profile (---) and σ_w Profile (-.-.-).

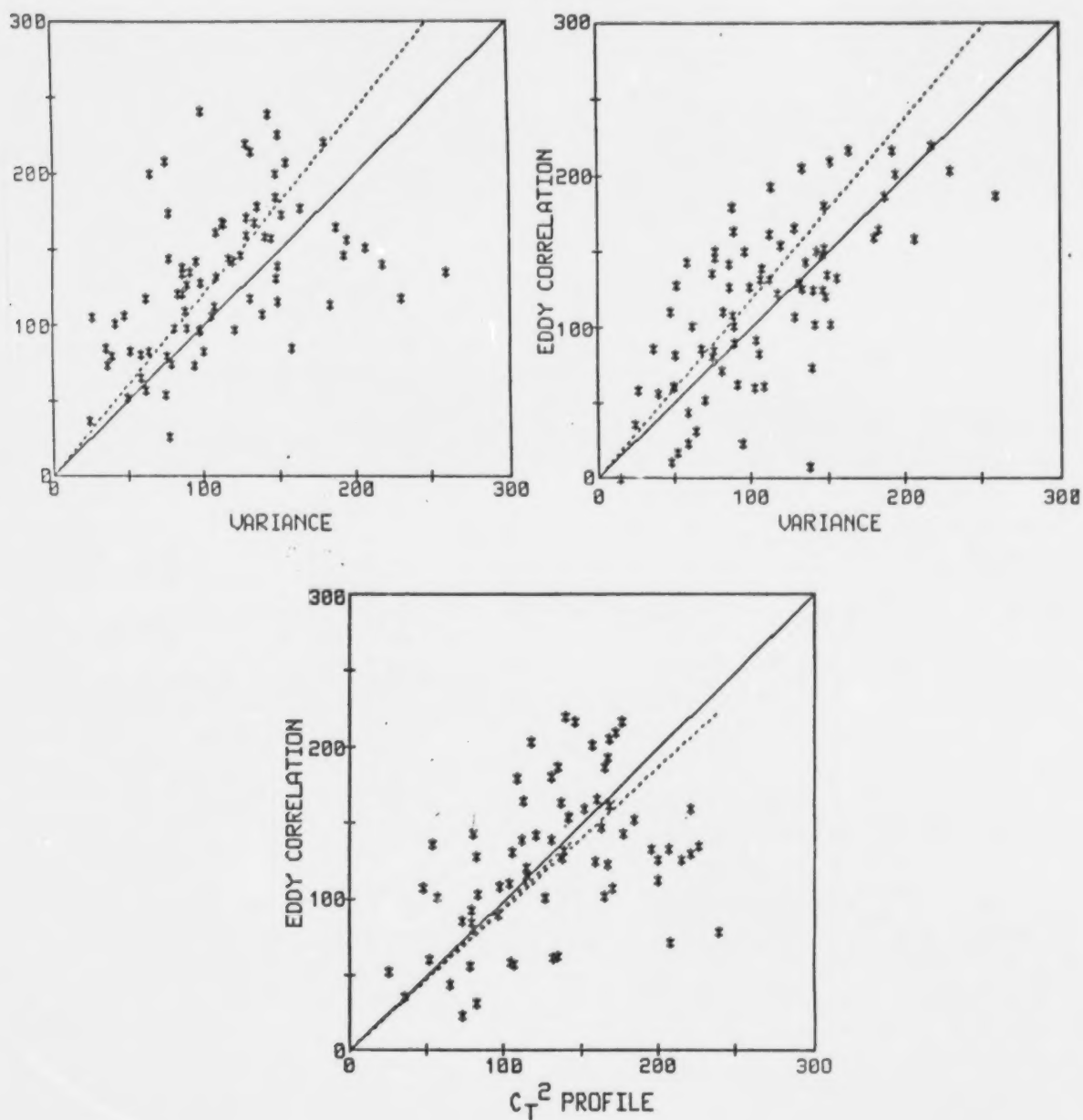


Fig. 3. Comparison of heat flux estimates from all days from the three methods. A 45 degree line (—) indicates one to one correspondence. Actual least squares fit is indicated by (---).

Table 1

X	Y	$\bar{X}$	$\bar{Y}$	σ_x	σ_y	Corr.	Coef.	SL (dx/dy)	INT
VAR	PROF	108	131	49	50	0.45	1.08	14.7	All PTS
VAR	E.C.	106	117	50	55	0.68	1.16	-6.0	"
PROF	E.C.	131	123	52	51	0.50	0.96	-2.2	"
VAR	PROF	112	118	52	53	0.58	1.05	0.8	NO MORNING PTS
VAR	E.C.	104	122	55	61	0.72	1.16	0.4	"
PROF	E.C.	114	130	55	57	0.66	1.06	8.9	"
VAR	PROF	105	128	32	40	0.57	1.82	-8	AVE. OF DAILY VALUES
VAR	E.C.	100	114	30	46	0.75	1.65	-25	"
PROF	E.C.	126	121	40	41	0.69	1.55	-15	"
ho	Z _I	451	435	271	289	0.87	1.08	-50	
ho	Z _I	447	575	270	337	0.84	1.30	-6.6	
Z _{IT}	X _{IB}	596	457	368	342	0.98	0.93	-9.6	

Perhaps the difficulty in obtaining sufficient averaging above the surface layer over periods of one hour is large enough to overshadow the beneficial volume-averaging effects. Much longer averaging times are not practical because of the strong diurnal trend of PBL structure.

It is interesting to note that all correlations are improved by ignoring morning values, although variance versus correlation is only improved by 0.04 while the profile method is improved by approximately 0.15 versus either of the other methods. The lines of best fit pass nearly through the origin and have slopes near 1.0, although the variance estimates are seen to be about 16% smaller than correlation estimates. When the average of the daily correlations is calculated, correlations are roughly the same as the overall statistics.

As stated above in regard to eq. (6), the buoyancy production of mechanical turbulence associated with water vapor flux is ignored in the present derivation of values of H_v . If included, the effect would be to lower the estimates of H_v by 10-20% on the average. Clearly, this works against the utility of the variance technique in producing reliable estimates of sensible heat flux at the surface, at least in the present set of data.

The variance method also allows the calculation of the height Z_I of the mixed layer through extrapolation of the least-squares line of σ_w^3/Z to the height h_0 of zero heat flux (Weill et al., 1980). Figure 4 and Table 1 show the comparison of these values with values of Z_I and of the height of the top of the entrainment layer (Z_{IT}) obtained from the facsimile display of sodar returns. An excellent correlation coefficient of 0.87 is found. However, the values of h_0 are seen to be slightly larger than those of Z_I rather than smaller. Much of this might be due to the range gate used (40 m) and resultant uncertainty, particularly for small values of Z_I ; in addition,

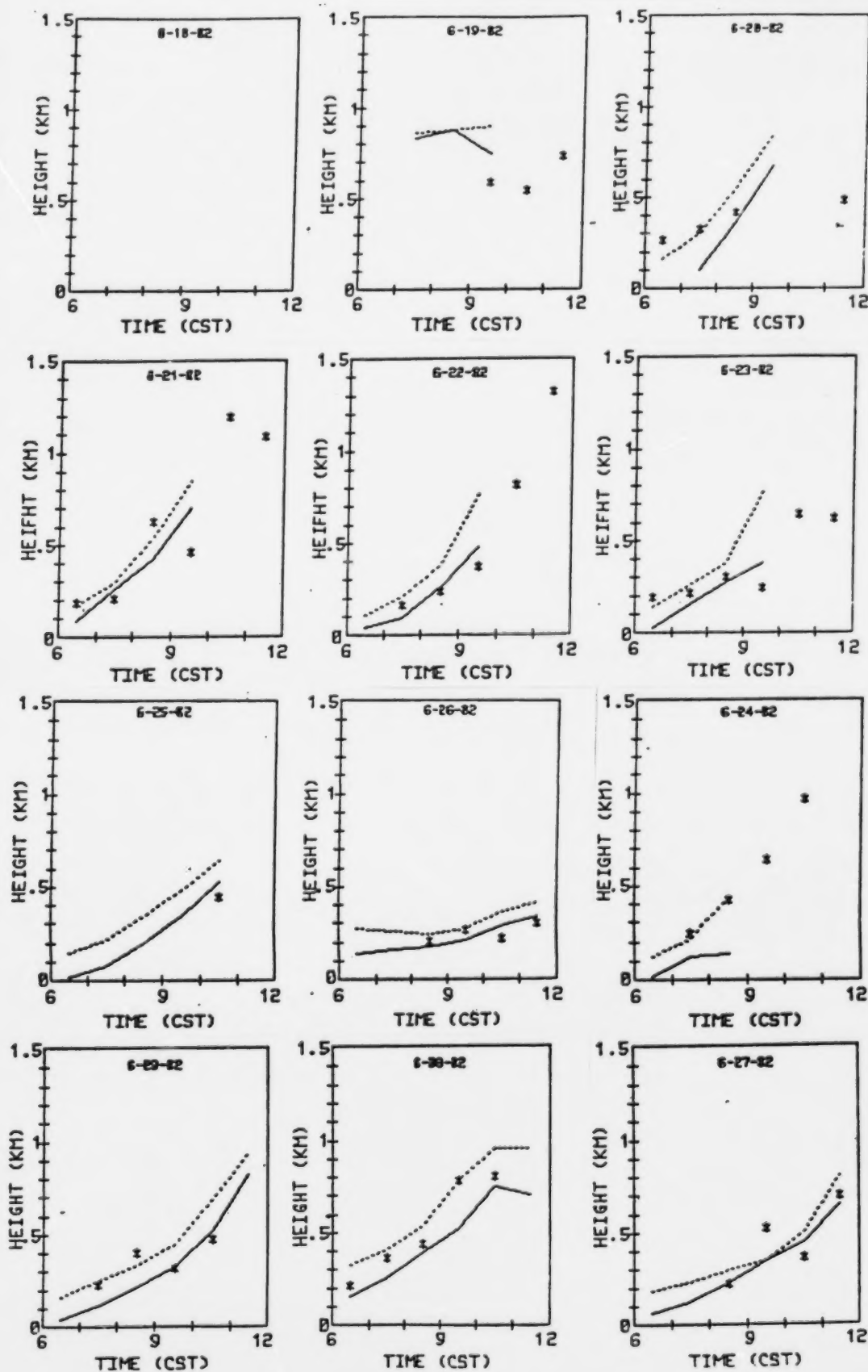


Fig. 4. Daily comparison of height of zero heat flux, h_0 , from the variance method (*) with the mixed layer height, Z_L (—) and top of the entrainment layer Z_{LT} (- - -) determined from the facsimile display.

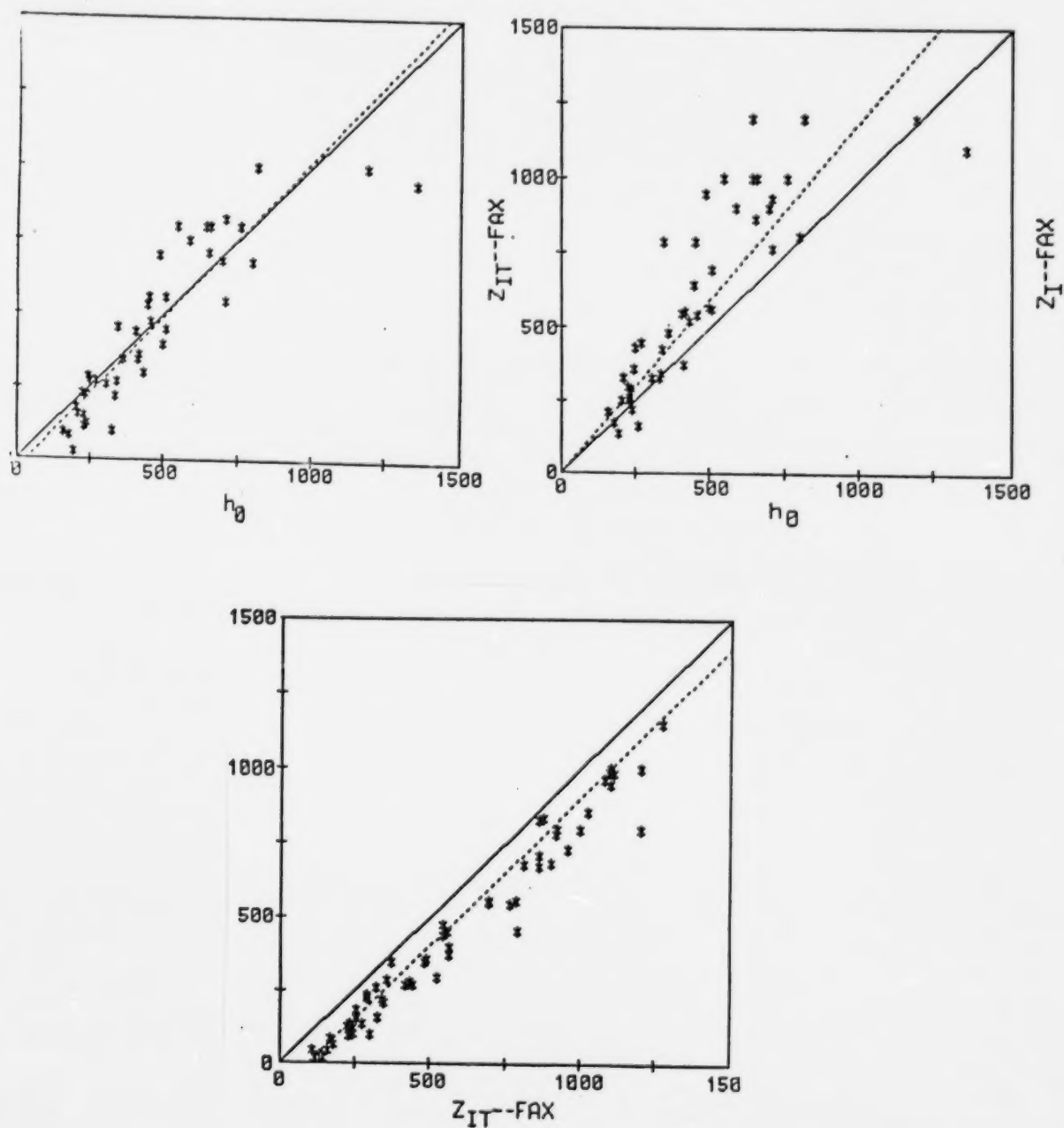


Fig. 5. Comparison of h_0 , Z_I and Z_{IT} for all days as in Fig. 3.

estimating values at large heights is difficult because the slope of $\sigma_w^{3/2}$ is close to zero. Another possible reason for the value of h_0 being large might be that the contribution of water vapor flux to buoyancy has been neglected. That is, since the water vapor flux remains fairly constant with height in the PBL, the intercept found where the heat flux is near zero might actually be the intercept where local $(H + 0.07 L_w E)$ goes to zero. However, in light of the numerous assumptions about the mechanical energy balance in the PBL that are used to derive eq. (6), no definitive remarks on the role of water vapor can be made at this time.

In summary, both the profile and variance methods for the calculation of surface heat flux are seen to give comparable results compared with point measurements. One might have expected better agreement between the two methods because of similar volume averages, but other factors are apparently important. It was necessary in this data set to limit the averages to one hour in order to coincide with the correlation measurements. As shown by Toconet and Weill (1983), this may not always be the appropriate time interval, particularly in the morning hours when the mixing height is rapidly changing. During this time period it is difficult to make any comparison among measurement techniques which require significant lengths of averaging time. Investigations into the possible effect of wind and/or temperature shear on the profile estimates as well as the possibility of local anisotropy of turbulence during a rapidly growing mixed layer can be carried out with this data set and a subsequent experiment undertaken recently in 1983.

5. ACKNOWLEDGMENT

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